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Technical Report No. 6

DETERMINATION of BEACH CONDITIONS by means of AERIAL PHOTOGRAPHIC INTERPRETATION

Volume IV

The CONE PENETROMETER as an INDEX of BEACH SUPPORTING CAPACITY (Moisture, Density and Grain-Size Relations)

Cornell University
Office of Naval Research

TECHNICAL REPORT NUMBER 6

DETERMINATION OF BEACH CONDITIONS

by means of

AERIAL PHOTOGRAPHIC INTERPRETATION

VOLUME IV

THE CONE PENETROMETER

as an INDEX of

BEACH SUPPORTING CAPACITY

In connection with
a contract between:

Amphibious Branch,
Office of Naval Research

School of Civil Engineering
Cornell University

U.S. Naval Photographic Interpretation Center, Monitor

Executed by the

Cornell Center for Integrated Aerial Photographic Studies

Beach Accessibility and Trafficability
Project No. NR 257 001
Contract N6onr, Task Order # 11

by

D. R. Lueder

D. J. Belcher, Director

June, 1954

Ithaca, New York

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KEY TO TECHNICAL REPORT NUMBER 6

Technical Report Number 6 is divided into five Volumes. The titles of these Volumes are as follows:

- Volume I - Relations Between Beach Features and Beach Conditions.
- Volume II - Variation and Stability of Beach Features (including an Appendix on Wave Tank Tests).
- Volume III - Photographic Gray Tones as an Indication of the Size of Beach Materials.
- Volume IV - The Cone Penetrometer as an Index of Beach Supporting Capacity (Moisture, Density and Grain-Size Relations).
- Volume V - A Method for Estimating Beach Trafficability from Aerial Photographs.

ACKNOWLEDGMENTS

The author expresses his appreciation for the cooperation, aid and helpful opinions provided by Colonel J. P. Stafford, U.S.M.C. and Major Carl Hill, U.S.M.C. both of the Amphibious Branch, Office of Naval Research and by Mr. Page Truesdell of the Naval Photographic Interpretation Center. The administration, establishment - and continuance - of this program is due in no small way to the efforts of these men.

Appreciation is extended to M. Tewfik, M. Malki, R. Morris and J. Schrauth for their efforts in completing the routine tests, computations and plots. Particular thanks are due M. Tewfik for bringing to the author's attention the results of his doctorate thesis insofar as they apply to the subject of this report.

Acknowledgment is due Professor Floyd O. Slate, who donated his time in helping to design the tests and in critically reviewing the entire manuscript.

Finally, credit belongs to Barbara Freeman for completion of the tedious task of report preparation and assembly.

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LIST OF FIGURES

CAUTIONARY NOTE

It is the ultimate objective of this research program to investigate and report upon a method for estimating beach trafficability by means of aerial photographic analysis. Trafficability is a tenuous term. For the purpose of this study, it has been considered to be related to:

1. Slope of beach
2. Bearing capacity of beach

Outside factors such as vehicle types, loads and tire pressures; driver abilities and surf conditions; and multiple pass effects were not considered.*

Two things must be emphasized. First, the trafficability diagram appearing as Figure 2 of Volume I and mentioned thereafter, relates slope and penetration values and assigns any given beach to one of five classes. THIS DIAGRAM IS INDICATIVE ONLY AND SHOULD NOT BE USED WITHOUT VERIFICATION OR MODIFICATION IN THE LIGHT OF CURRENT OPERATIONAL TECHNIQUES.

Secondly, the index of beach sand bearing capacity chosen by the authors for use in this investigation was constant weight penetration. The authors believe this to be a reasonable and acceptable index.** However, THE SIGNIFICANCE OF THE INDEX WITH RESPECT TO ACTUAL OPERATIONS MUST BE EVALUATED BY USING AGENCIES.

These statements emphasize the necessity for studies which will correlate penetrations with operating conditions. Only by this means can the research results discussed in Technical Report #6 by utilized to their fullest extent.

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* See Progress Report #1, "Relations Between Beach Features Visible on Airphotos and Beach Trafficability".

** See Volume IV (Key).

LIST OF ABBREVIATIONS

AFS	- Average foreshore slope (See Appendix A)
APR	- Average penetration reading
Bs	- Backshore
d	- Divergence (See Figure 10)
D_{50}	- Median grain-size (See Figure 10 and Appendix A)
Dec D_{50}	- Decimal median grain-size (See Figure 10)
DFs	- Drying foreshore
Fs	- Foreshore
Fs MSLW	- Foreshore mean-sea-level width (See Figure 9b and Appendix A)
PR	- Penetration readings
WFs	- Wetted foreshore

SECTION I

INTRODUCTION

SCOPE OF VOLUME

This volume is concerned with the factual aspects of one subdivision of a current research project conducted for the Amphibious Branch, Office of Naval Research. It describes the results obtained from a series of laboratory tests designed to indicate the relations between constant weight penetration, moisture content, density and median grain-size of selected beach sands.

A series of conclusions appears as SECTION III. The conclusions are based on the data, analyses and discussions included herein. Consequently, they represent the specific conclusions of the report - not conclusions of the complete research program.

Final conclusions of the complete research program will be limited in nature. Only those factual aspects that are pertinent to the ultimate objectives of the program will appear. These will be included in Volume V.

SPECIFIC OBJECTIVE OF VOLUME

The primary objective of this Volume, as mentioned in SCOPE, is the study of relations between constant weight penetration, moisture content, density and median grain-size of beach sands. More specifically, its purpose is to show - in general - whether constant weight penetration provides a usable index of the supporting capacity of beach sands.

ULTIMATE OBJECTIVES OF
COMPLETE RESEARCH PROGRAM

The ultimate objectives of the complete research program are:

1. The presentation of relations between physical features (visible on aerial photographs) that are associated with beaches, and the trafficability of beaches.*

2. The formulation, based upon such relations, of a method for estimating the trafficability conditions of beaches from aerial photographs.

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* See CAUTIONARY NOTE

PROBLEMS OF RESEARCH

There are numerous features associated with beaches that may have some relation to trafficability and that can also be seen on aerial photographs. These are:

1. Details of beach profile (width, slope, cusps, scarps)
2. Wave and surf features (length, frequency, shape, direction, refraction, breaker patterns)
3. Gray tones (beach sands, moisture holding capacity, turbidity stains, depth differences)
4. Environmental features (offshore and onshore protection, river mouths, sources of supply, indications of littoral current flow)
5. Miscellaneous features (current ripples, bars)

These features, as well as trafficability itself, reflect the interaction of numerous variables. The variables are:

1. First order variables (independent)
    a. Location and variations in winds
    b. Environment
        (1) Protective underwater features
        (2) Protective surface features
        (3) River and tidal mouths
        (4) Littoral currents
        (5) Geological sources and types of materials that contribute to beach

(6) General offshore slope

c. Tides

2. Second order variables (dependent upon first order)

    a. Wave characteristics and variations

3. Third order variables (dependent upon first and second order)

    a. Variations in local offshore slopes, bars and local material supplies.

None of these variables can be controlled by any normal means. Few can be evaluated easily by instrumental devices. Consequently, it is difficult to relate specific beach features to the variable or combination of variables that produce them. To satisfy the practical requirements of the project, it was decided to subordinate the relations between beach features and their causative variables and to emphasize direct relations between features and trafficability conditions.

SCHEME OF COMPLETE RESEARCH PROGRAM (CURRENT)

The current program was subdivided into various separate activities. This was done in an attempt to circumvent some of the difficulties previously discussed by varying the direction of attack.

The subdivisions established were as follows:*

1. Routine Beach Observations

   The collection of routine observations at permanent beach stations for a reasonable period of time. This phase was designed to give information concerning the changes of beach features and conditions on beaches of various types <u>over a period of time</u>. This phase, since it was concerned with time, was expected to throw some light on the relative importance of causative variables such as waves, material characteristics, etc.

2. Empirical Beach Survey

   The collection and analysis of information concerning the physical and penetrometer profiles and the sand characteristics of various beaches picked at random. This phase, since it neglected time, waves and environment, was designed to provide relations between <u>visible features and trafficability conditions regardless of any causative variable except beach materials</u>.

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* See Key at beginning of this Volume.

3. PENETRATION - COMPACTION STUDIES (SUBJECT OF THIS REPORT)

   A SMALL LABORATORY STUDY OF THE RELATIONS BETWEEN PENETROMETER READINGS, COMPACTION AND GRAIN CHARACTERISTICS.

4. Wave Tank Investigation

   A small investigation of general relations between slope, slope variations and relative stability as affected by changes in the characteristics of waves acting upon materials of different grain-size.

5. Gray Tone Studies

   A densitometric study of gray tones on the beach as indicators of predominant sizes of beach materials and their relative firmness.

Each of these subdivisions will be treated in subsequent reports.

SECTION II

RELATIONS BETWEEN PENETRATION, DENSITY, MOISTURE CONTENT SATURATION AND GRAIN-SIZE

GENERAL

As emphasized in the CAUTIONARY NOTE, the primary objective of the current research program is the estimation, from aerial photographs, of the capacity of beach sands to support vehicle movement.

Other parts of Technical Report Number 6* relate physical beach features that are visible on aerial photographs to an index of this capacity. The index chosen for the study is penetration (taken with a constant weight penetrometer).**

It is the purpose of this section of this report to show that, in general, penetration is truly an index of this capacity. It is not the purpose of the report to present a detailed mathematical-empirical analysis of constant weight penetration as an indicator of the various factors which are incorporated in the capacity of beach sands to support vehicle movement. Such an objective would require a separate research program of a fairly ambitious nature.

The capacity to support vehicle movement implies the combined effect of:

1. Bearing capacity of the beach sand
2. Tractive capacity of the beach sand
3. Rolling resistence of the beach sand

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* See Key at front of report

** See Technical Report Number 5, "The Use of Penetration Devices on Beaches", March 1952.

Bearing capacity may be defined as the "largest intensity of pressure which may be applied --(by a tire or track)-- to the soil without causing excessive settlement or danger of failure to the soil in shear".*

Tractive capacity may be defined as the sum of average horizontal passive resistance and frictional force that is developed by the soil in reaction to the horizontal components of tread traction - and which enables tread traction to propel a vehicle.

Rolling resistance may be defined as the sum of complex passive and frictional resistance to displacement, in excess of densification, that is developed by a soil in front of a wheel whose treads are lower than the surrounding soil surface.**

It can be shown that each of the above capacities is related to the shearing strength of the soil. <u>Consequently, it is the purpose of this section to demonstrate that penetration is related to the shearing strength of the soil.</u>***

The major criteria of soil strength are called "cohesion" and "internal friction". Cohesion expresses the resistance to shear afforded by the intrinsic pressure that exists within a soil mass by virtue of:

---

* Taylor, D.W., Fundamentals of Soil Mechanics, John Wiley & Sons, 1948.

** The implication of these terms is described at some length in Manual of Amphibious Oceanography, Section V, "Beach Trafficability and Stabilization", Univer. of Calif., 1952.

*** Because of budget limitations, it was not feasible to correlate penetration and shear strength (by means of direct or triaxial shear tests).

1. Complex physico-chemical bond (true cohesion)
2. Capillary physico-chemical bond (apparent cohesion)

Sands may be assumed to have no true cohesion, but may have considerable apparent cohesion due to the capillary bond. The capillary bond depends upon the amount of moisture within the soil pores, i.e., it is a function of moisture content, grain-size distribution, and grain-shape distribution.

Internal friction expresses the combined physical resistance to shear that is afforded by the tendency of individual grains of the soil mass to resist rolling and sliding and the effect of interlocking between such individual grains. It is largely a function of density, grain-size distribution and grain shape distribution (plus applied load).

In view of the above discussion it may be said that the shearing strength of beach sands may be expressed in terms of apparent cohesion* and internal friction, and that these factors may be expressed in terms of:

* In many soil mechanics theories, strength due to apparent cohesion is neglected due to its transitory nature. On the drying foreshore of beaches, it may be expected to provide an amount of shearing strength which varies from a maximum at a certain moisture content to minimums at some other moisture contents. At its maximum, the apparent cohesion may be expected to provide a significant amount of shearing strength.

1. Density of the sand*
2. Moisture content of the sand*
3. Grain characteristics of the sand*
    a. Size-distribution
    b. Shape-distribution

Consequently, it becomes the purpose of this section to show, in a general way, that penetrations reflect, to a significant extent, significant variations in the density, moisture content and grain characteristics of beach sands. If this can be shown, then it can be presumed that penetrations reflect variations in the shearing strength of beach sands -- and in consequence, that penetrations provide a usable index of the capacity of beach sands to support wheel loads without excessive deformation, i.e., an important element of beach "trafficability."

---

* For example, Taylor's modification of Prandtl's analysis for a long strip footing:

$$qu = \left(\frac{c}{\text{Tan } \phi} + \frac{wb\sqrt{K_p}}{2}\right)\left(K_p E \pi \text{ Tan } \phi - 1\right)$$

where

qu = ultimate bearing capacity
c = cohesion of soil
w = weight of soil (density)
b = width of footing
ϕ = angle of internal friction of soil (a function of grain characteristics, density and normally applied load)
$K_p = \dfrac{1 + \sin \phi}{1 - \sin \phi}$
E, π = constants

MOISTURE-DENSITY-PENETRATION RELATIONS FOR VARIOUS SANDS

The following pages are concerned with actual relations, as determined by laboratory test, between the following quantities:

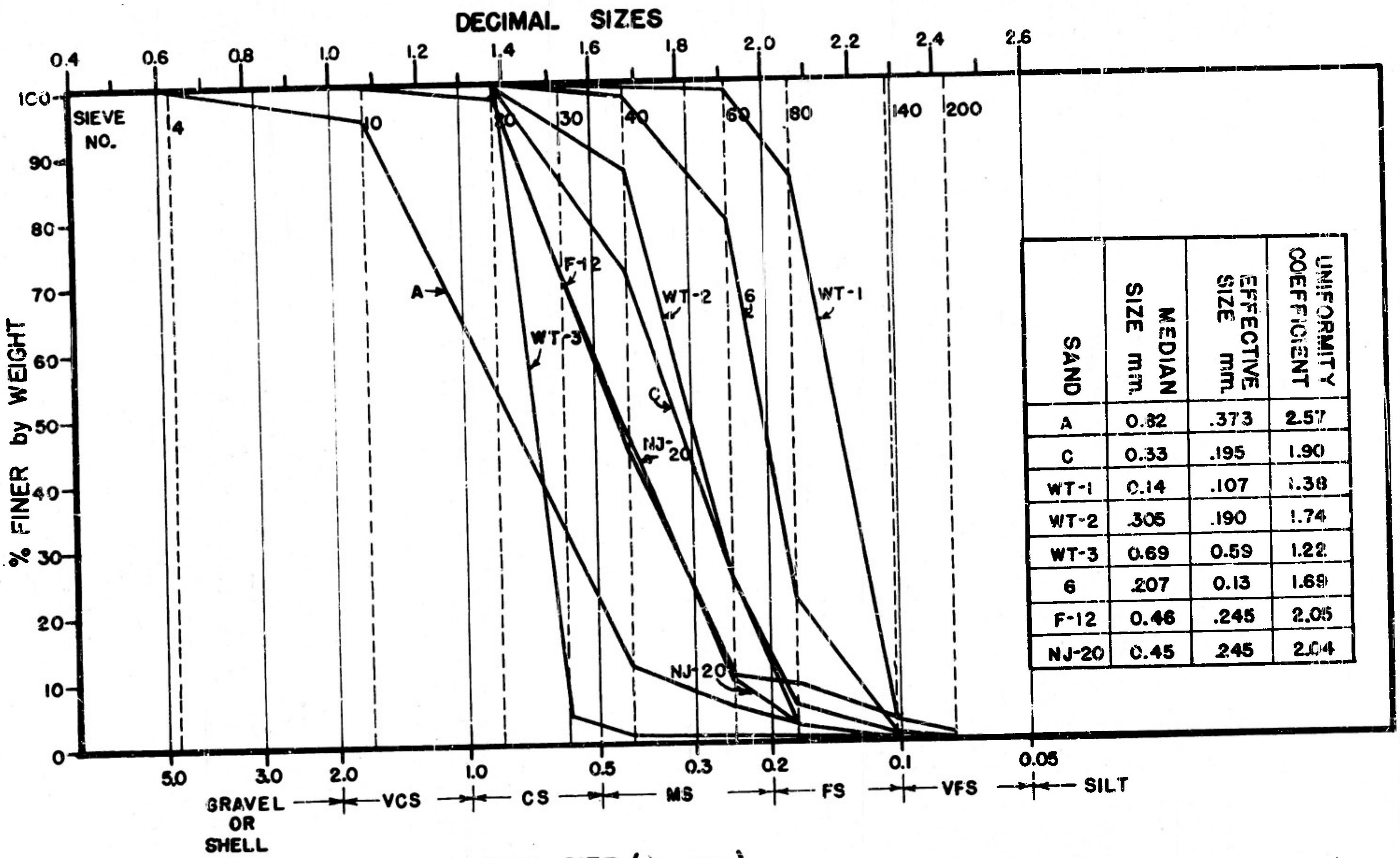
1. Penetration (PR)
2. Density (in terms of void ratio, e)
3. Moisture content (w)
4. Degree of saturation (S)
5. Median grain-size of sand (D_{50})

These quantities are defined by formula in Appendix B. The complete method of laboratory testing appears as Appendix A.

Nine sands (7 from actual beaches and 2 from non-beach deposits) were tested. Pertinent descriptive data for these sands is given in Figure 1.

The laboratory relations between the above factors, for all of the tested sands, are presented graphically in Figures 2 to 10. The figures are arranged in order of increasing median grain-size, relations for the finest sand appearing in Figure 2 and the coarsest in Figure 10. The plots are designed to show simultaneous values of PR, e, w and S for each sand.

Values of the moisture content (w_{t_a}), plotted along the horizontal axis, refer to moisture contents at the top of the mold. The values of "PR" refer to penetrations at the top of



SAND	MEDIAN SIZE mm.	EFFECTIVE SIZE mm.	UNIFORMITY COEFFICIENT
A	0.82	.373	2.57
C	0.33	.195	1.90
WT-1	0.14	.107	1.38
WT-2	.305	.190	1.74
WT-3	0.69	0.59	1.22
6	.207	0.13	1.69
F-12	0.46	.245	2.05
NJ-20	0.45	.245	2.04

FIGURE 1 - GRAIN SIZE DATA FOR TESTED SANDS

the mold. The values of "e" refer to the presumed* void ratio at the top of the mold. The values of "S" are based upon the moisture content at the top in relation to the presumed void ratio at the top.

The plots for each sand consist of one involving penetrations taken with no surcharge on top of the sand and one involving penetrations with an annular surcharge surrounding the point of penetration. The reason for this double plot will be discussed later.

The ranges of values included on each plot exceed the field ranges. The field ranges include 90% of the actual moisture contents, void ratios and median grain-sizes actually found in the survey of Atlantic Coast beaches.** The actual values are given in Table I.

---

* The value of "e" depends upon the value of "w" chosen for its computation. The value of "w" used in this study was the average moisture content in the mold computed according to Simpson's Rule for 3. While the moisture between the top and middle of the mold may vary appreciably (and not uniformly), particularly for coarse sands, there is no reason to believe that the void ratio will vary proportionally. Assuming no appreciable grain segregation with depth, the only two things that would tend to cause a variation in voids from top to bottom would be the effect of moisture drawn down or the effect of non-uniform compactive effort on the multiple layers in the mold. The first factor may be disregarded. The second factor may be expected to have an effect, such that the middle and top layers are slightly more dense than the top. In this study, the difference was assumed negligible largely because no method of determining actual differences was available.

** Part I in Key at front of report.

TABLE I

ACTUAL FIELD RANGES OF VARIOUS PERTINENT FACTORS

Type Sand	Arbitrary Size Limits (mm)	D_{50} (mm)	Void ratio (e)	Moisture (%)	Saturation (%)
Fine	0.1-0.2	0.13-0.2	0.60-0.90	2-25	10-95
Medium (fine)	0.2-0.3	0.2-0.3	0.65-0.85	2-25	10-90
Medium (coarse)	0.3-0.5	0.3-0.5	0.70-0.75	2-10	5-25
Coarse	0.5-1.0	0.5-0.66	0.50-0.75	2-8	5-25

Figures 2 to 10 show that all of the test sands tend to have a similar characteristic plot. For any given sample, there is an infinite number of moisture-density combinations that will yield a given penetration, the lines of combinations following a generally similar geometrical pattern. The general shape of this apttern apparently transcends grain-size.

It is necessary to emphasize that the lines of equal PR represent the center of narrow zones rather than lines of mutual exclusion.

It is interesting to note the similarity between Figures 2 to 10 and 11. This latter figure is copied from a PhD thesis by Dr. Mohammed Mohsen Tewfik* and, for a Dunkirk silty clay, shows the coincident values of void ratio, moisture content, degree of saturation and unconfined compressive strength.

* The Strength of a Clay as a Function of its Density Characteristics and Degree of Saturation, School of Civil Engineering, Cornell University, 1953.

The obvious similarity between Figures 2 to 10 and 11 supplies the basis for the following statements:

1. There may be a similarity between the unconfined compressive strength of cohesive soils and the penetration of cohesionless sands.
2. Penetration may be an index to the shearing (unconfined compressive) strength of cohesive soils.
3. Penetration may be an index to the shearing strength of sands.
4. The moisture-density-shear strength relationships of cohesive and cohesionless soils may be analagous in general.
5. Lines of equal shearing strength (cohesive soils) and penetration (cohesionless soils) result from an infinite number of moisture-density combinations, not from a single combination for any desired strength.

Considering these statements in turn:

1. The acceptance of statement 1 is based merely upon an acceptance of Figures 2 to 11 as true representations of relations between the several factors under laboratory conditions. Objections might be raised due to the extrapolation of some of the curves. There is no special justification for such extrapolation beyond the usual reasons:

a. An indicated trend in terms of other tests and in terms of scattered points within the same test

b. Best fit of the plotted data

c. Reasonable extension of observed experience

Some of the plots (Sands C and F-12) include a substantial number of points which do not agree with the indicated lines. In F-12, the discrepancies are confined to one compactive effort (dropping on edges). In view of the other consistencies in this test, this series is presumed to be in error. The discrepancies of sand C are not easily explained. They may have been caused by less than usual care in taking penetrations. It is also pointed out, as before, that if the lines be considered the center of zones, the discrepancies appear less serious.

2. This statement follows from an acceptance of statement 1. However, there is other supporting evidence. In a bulletin issued in 1948 by the Corps of Engineers*, the conclusions include the following statement:

> "The numerical value of the cone index is roughly four times that of the unconfined compressive strength except for moisture contents below about the plastic limit."

---

* "Trafficability of Soils - Laboratory Tests To Determine Effects of Moisture Content and Density Variations", Technical Memorandum No. 3-240. First Supplement, Waterways Experiment Station, Corps of Engineers, March 1948.

The tests to which this statement refers were made on cohesive soils only (unconfined compression being impossible for cohesionless soils) and were made with a much smaller cone (1 in^2 projected area, 2.1 inches high, versus 7.07 in^2, 8.5 inches high for the constant weight instrument). Since the unconfined compression is a measure of shearing strength (particularly for clays), statement 2 appears acceptable.

3. This statement follows from an acceptance of 1 and 2. It has little corroborative evidence beyond that of the similarity among Figures 2 to 10 and Figure 11. Although this similarity is significant, the subject will be treated at greater length in following pages by considering the relationship between penetration and density, moisture and grain-size. The publication referred to above showed a correlation between cone index and CBR even for non-plastic soils. Consequently, a correlation between cone index and shearing strength may be inferred. It is unfortunate that the tests conducted by the Engineers did not include any direct data on the shearing strength of non-plastic soils.

4. This statement follows from the preceding statements and appears rational from an experience standpoint. The words "<u>in general</u>" are important. Cohesive soils possess true cohesion. Cohesionless soils do not (although they may have apparent cohesion that cannot be neglected in the usual manner). Therefore, it may be expected that the relationships are not

identical or even parallel. The similarity of Figures 2 to 10 and 11, as well as considerations of density and moisture in general, indicate that this statement is correct.

5. This statement follows from the preceding statements. It is included to emphasize the indications that strength results from a variable combination of density and moisture content and not from a single combination (maximum density at optimum moisture, for example)*.

Some authors have expressed an opinion to the effect that penetrations might not prove to be a valid index of beach sand supporting capacity because they measured the sand in an unconfined state. They argued that a wheel, by exerting a confining effect upon the sand, increased its shearing strength appreciably.

To investigate the effect of surface confinement upon the penetrations obtained in beach sands, a series of tests was completed using a CBR annular surcharge. The results of these tests, included in Figures 2, 4, 5, 7 and 8 show that for any given moisture-density combination, the penetration was lower with a surcharge than without, i.e., the shearing strength was greater. However, the use of the surcharge had little effect upon the general nature of the pattern and consequently, little effect upon the use of penetrations as a valid index of supporting capacity.

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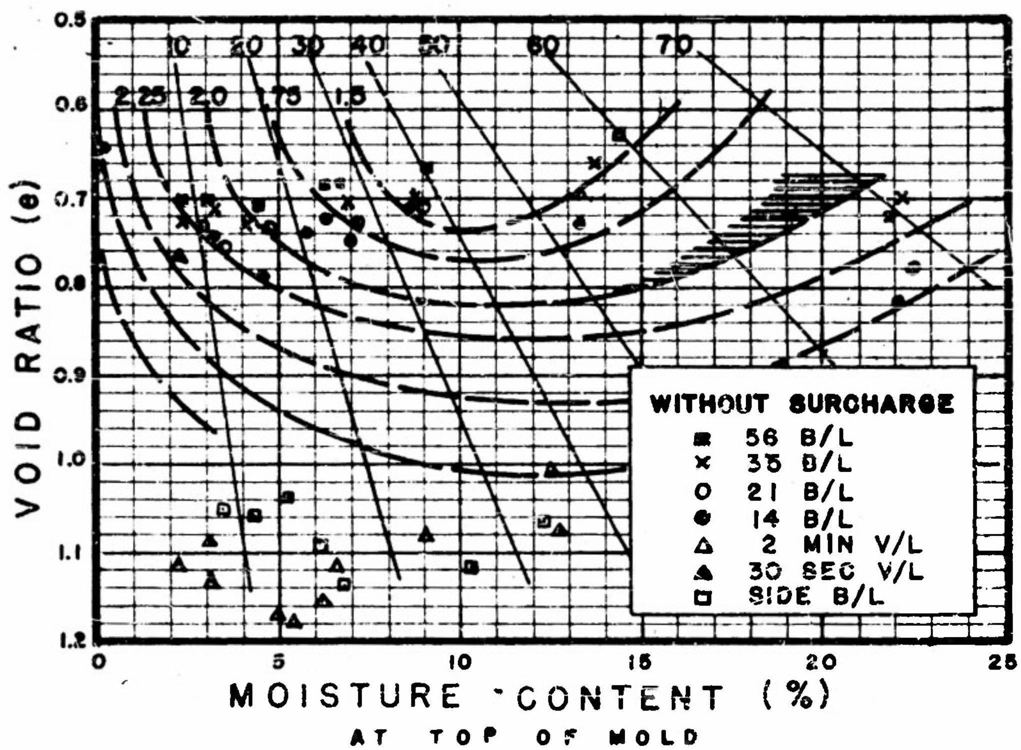
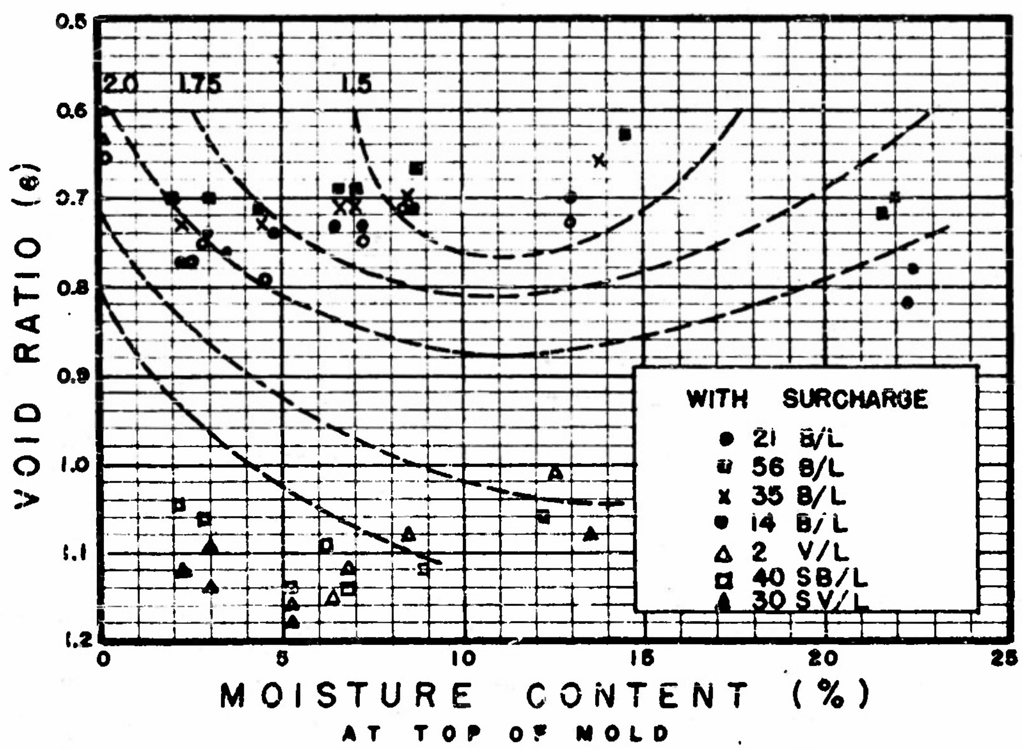
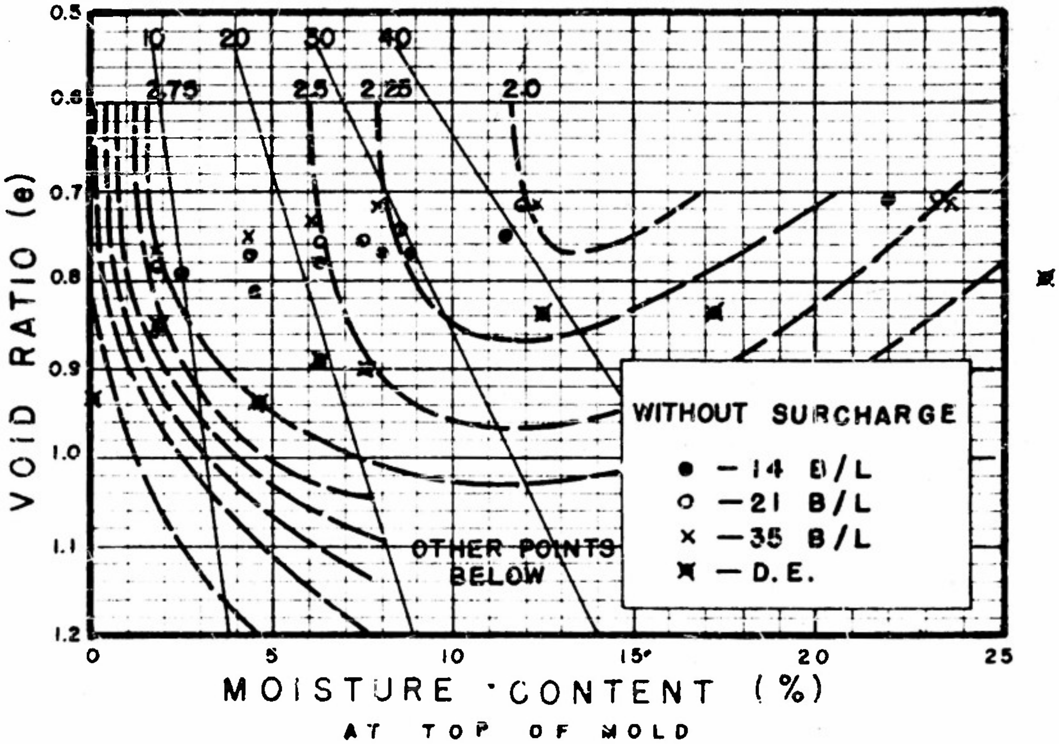
* For some interesting data on this subject, see "Some Relationships Between Density and Stability of Subgrade Soils", Seed, H.B. and Monismith, C.L., Proceedings, Highway Research Board, 1953.

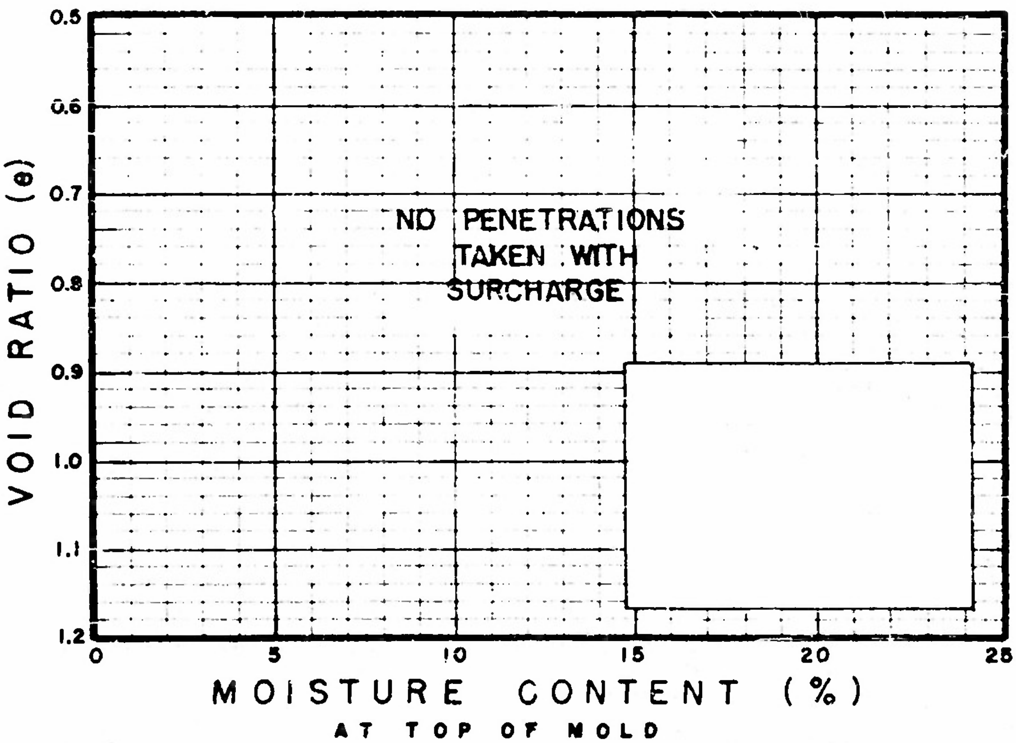




RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND WT-1

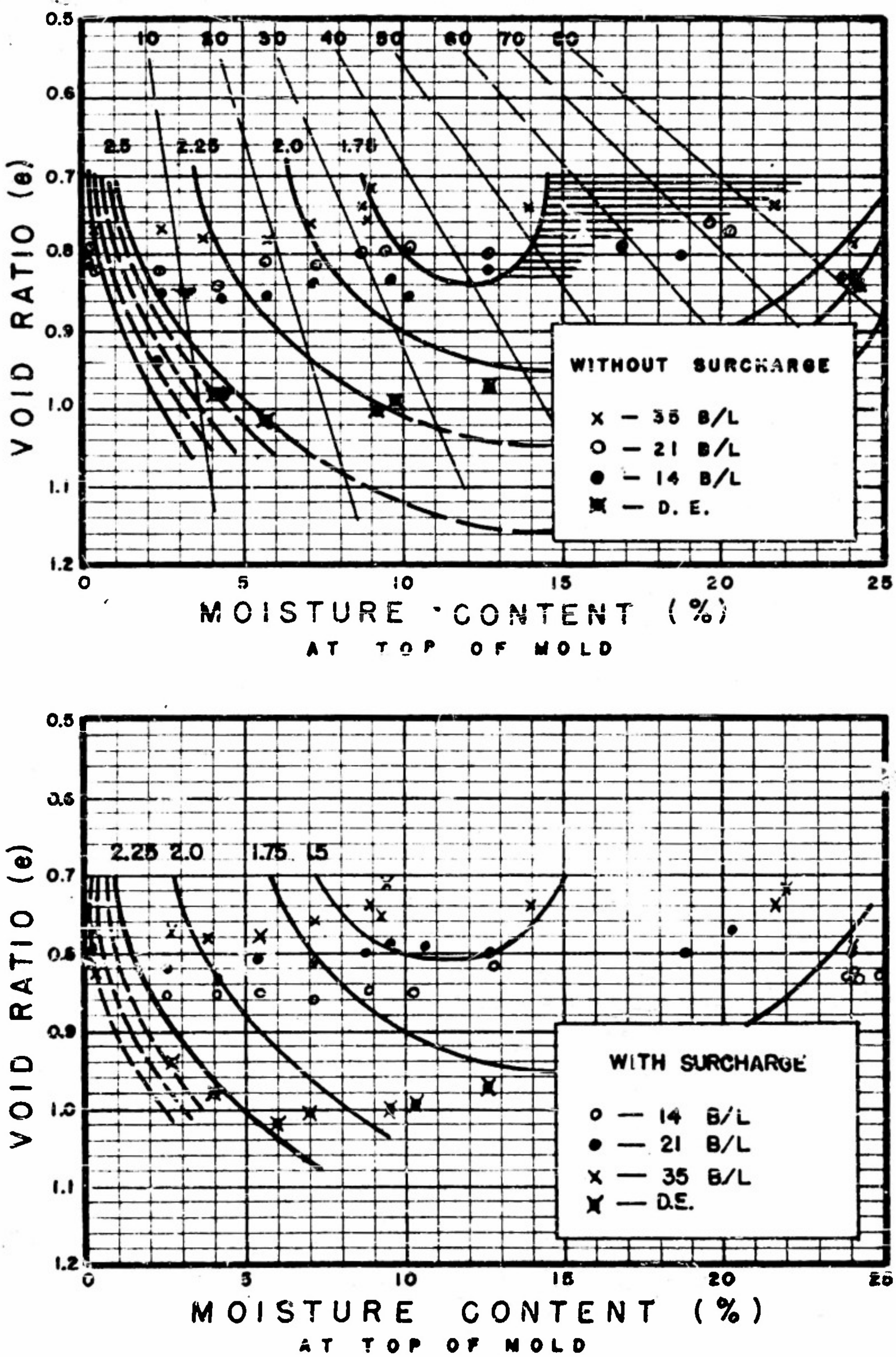
FIGURE 2





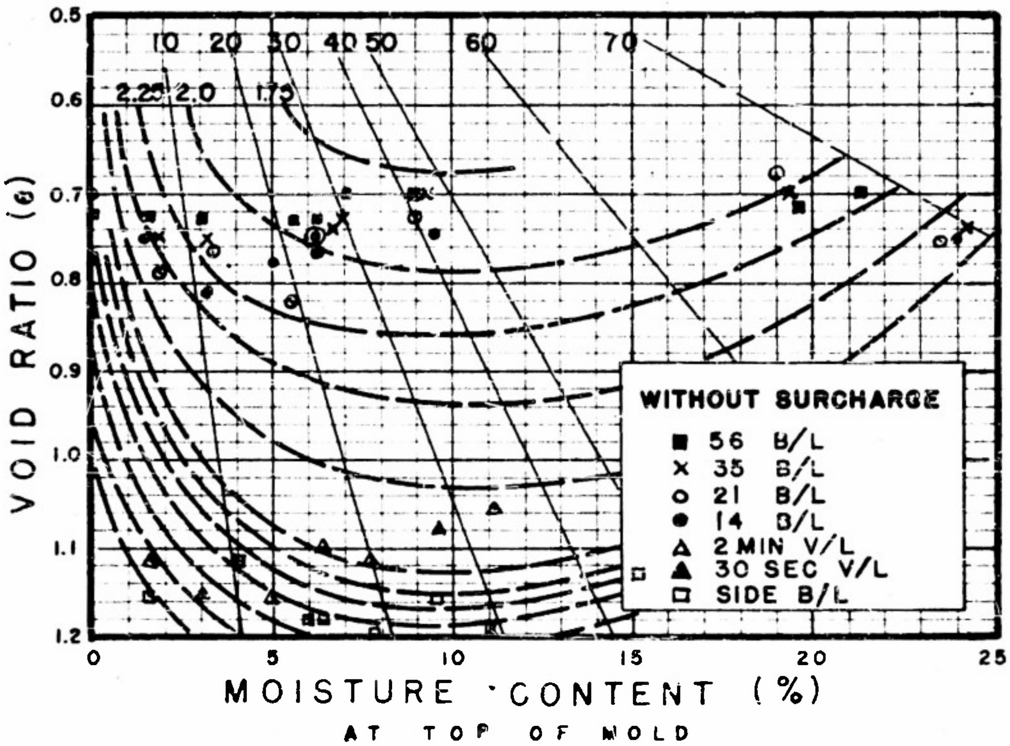
RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND B

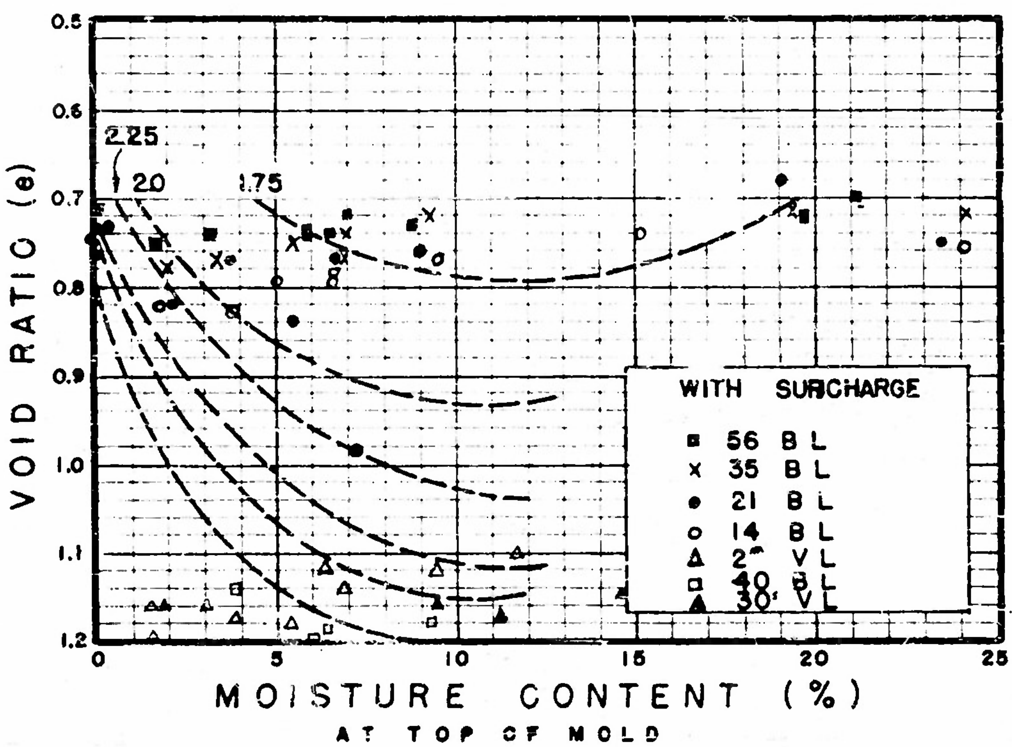
FIGURE 3



RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND 6

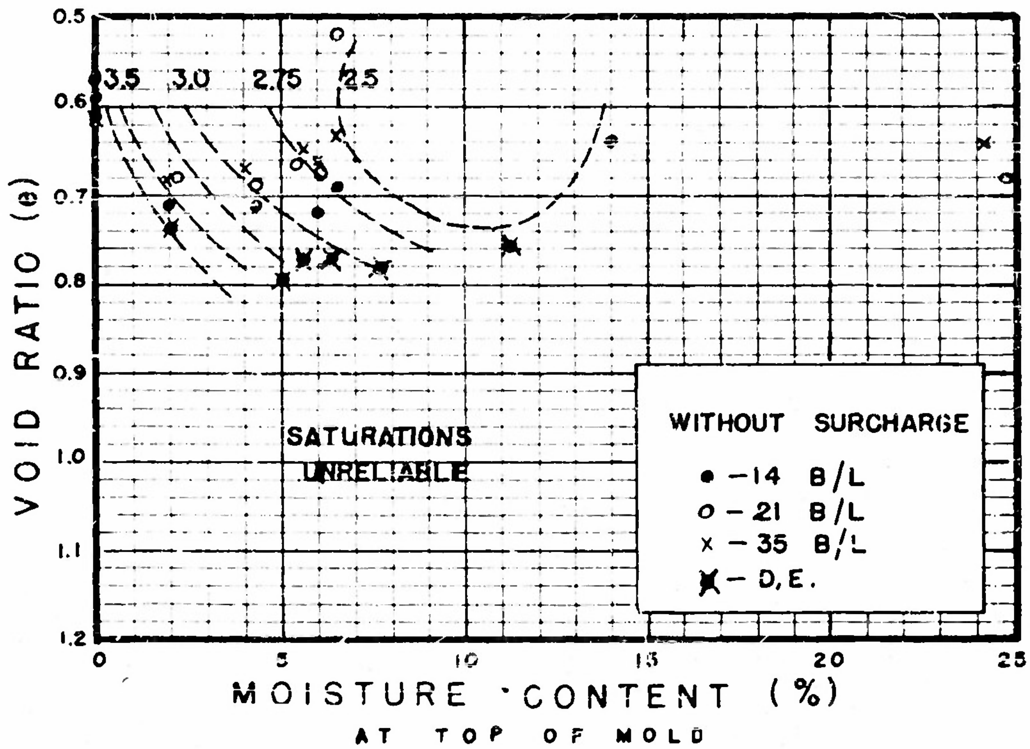
FIGURE 4

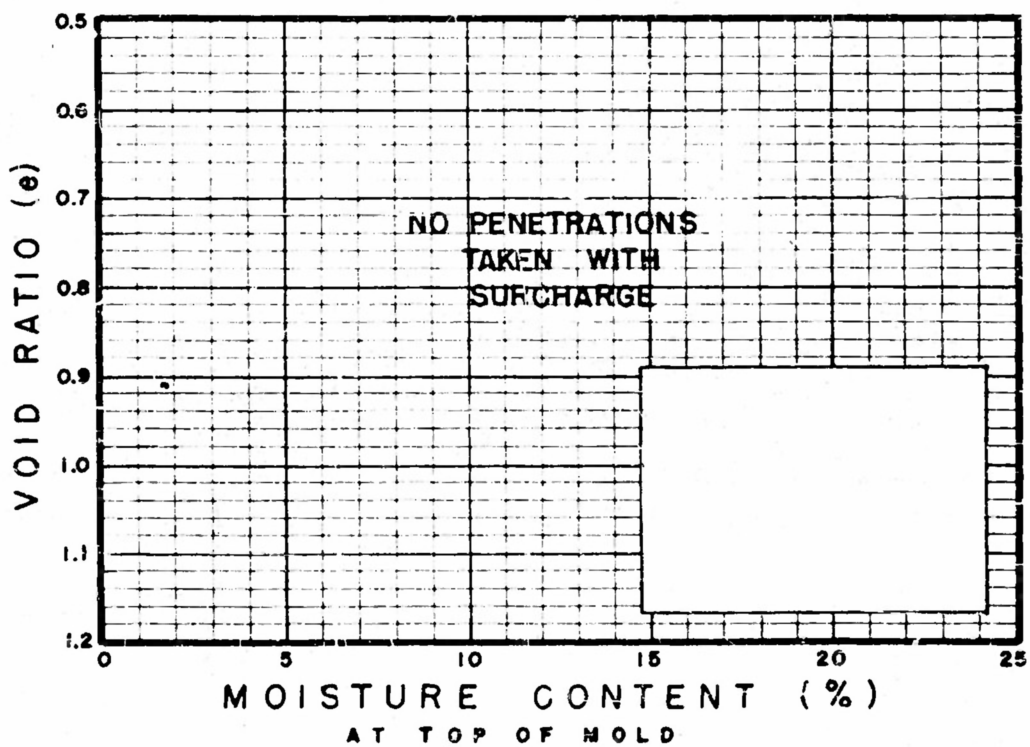




RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND WT-2

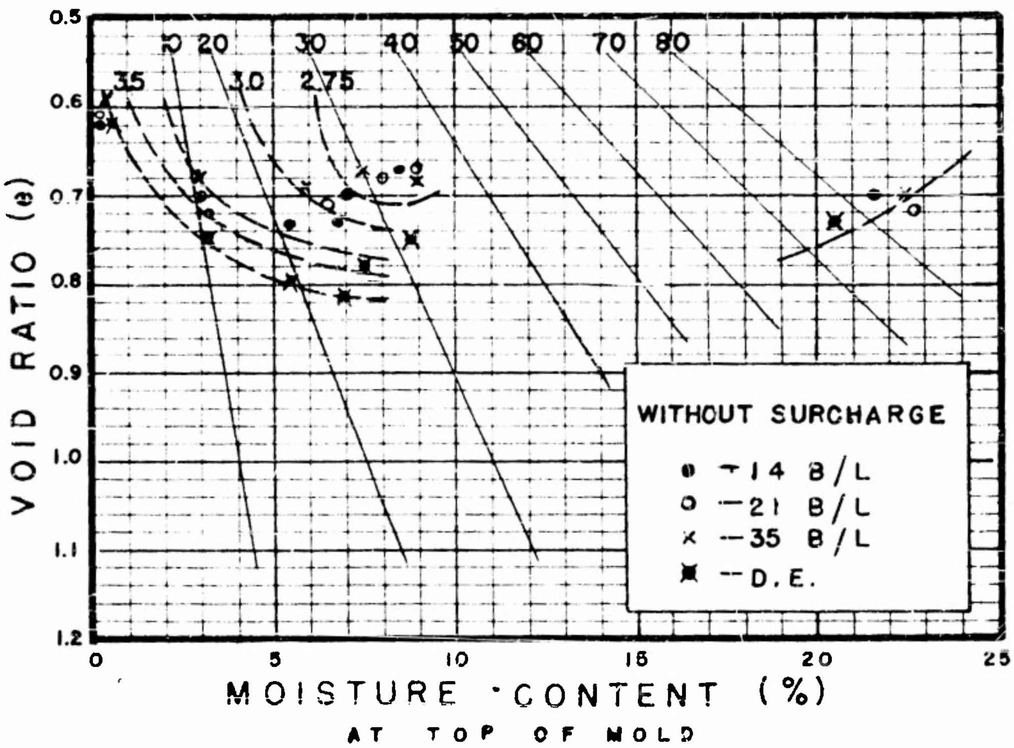
FIGURE 5

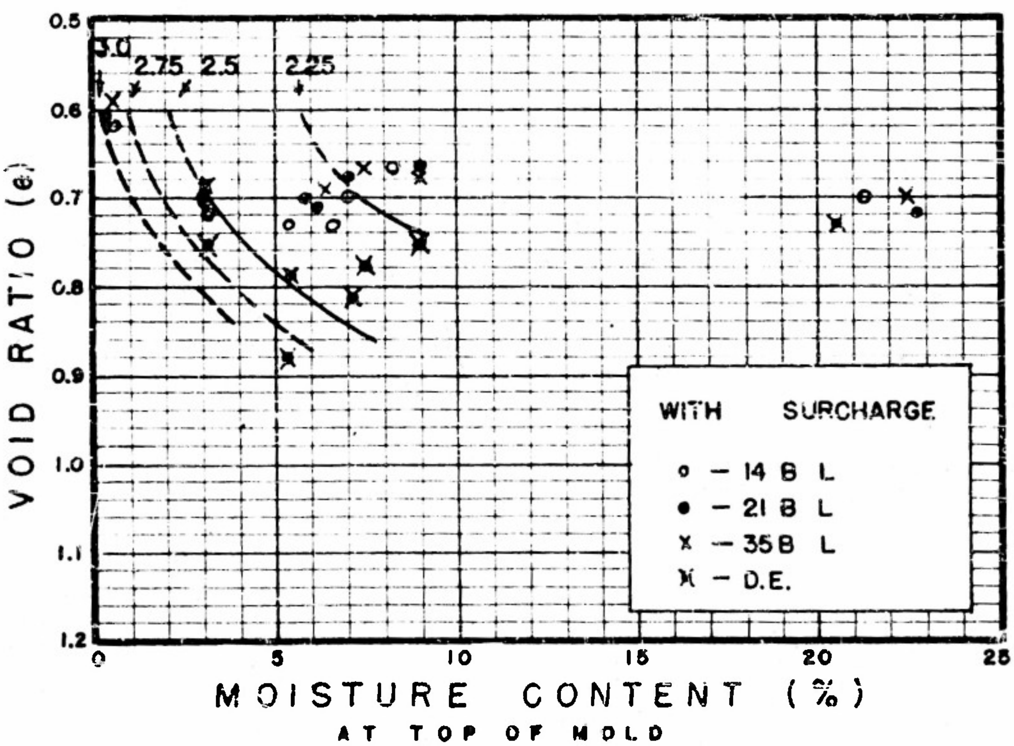




RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND C

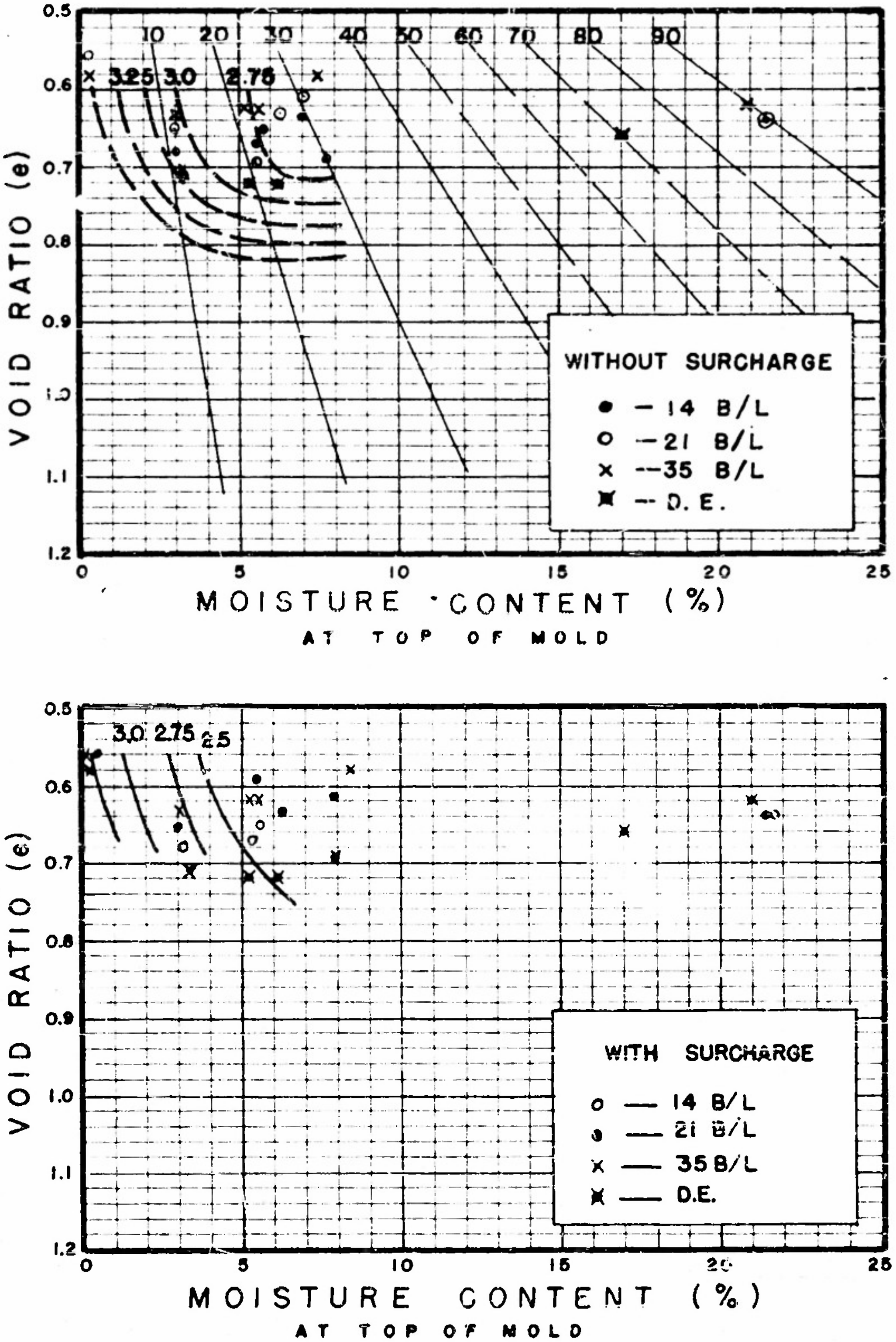
FIGURE 6





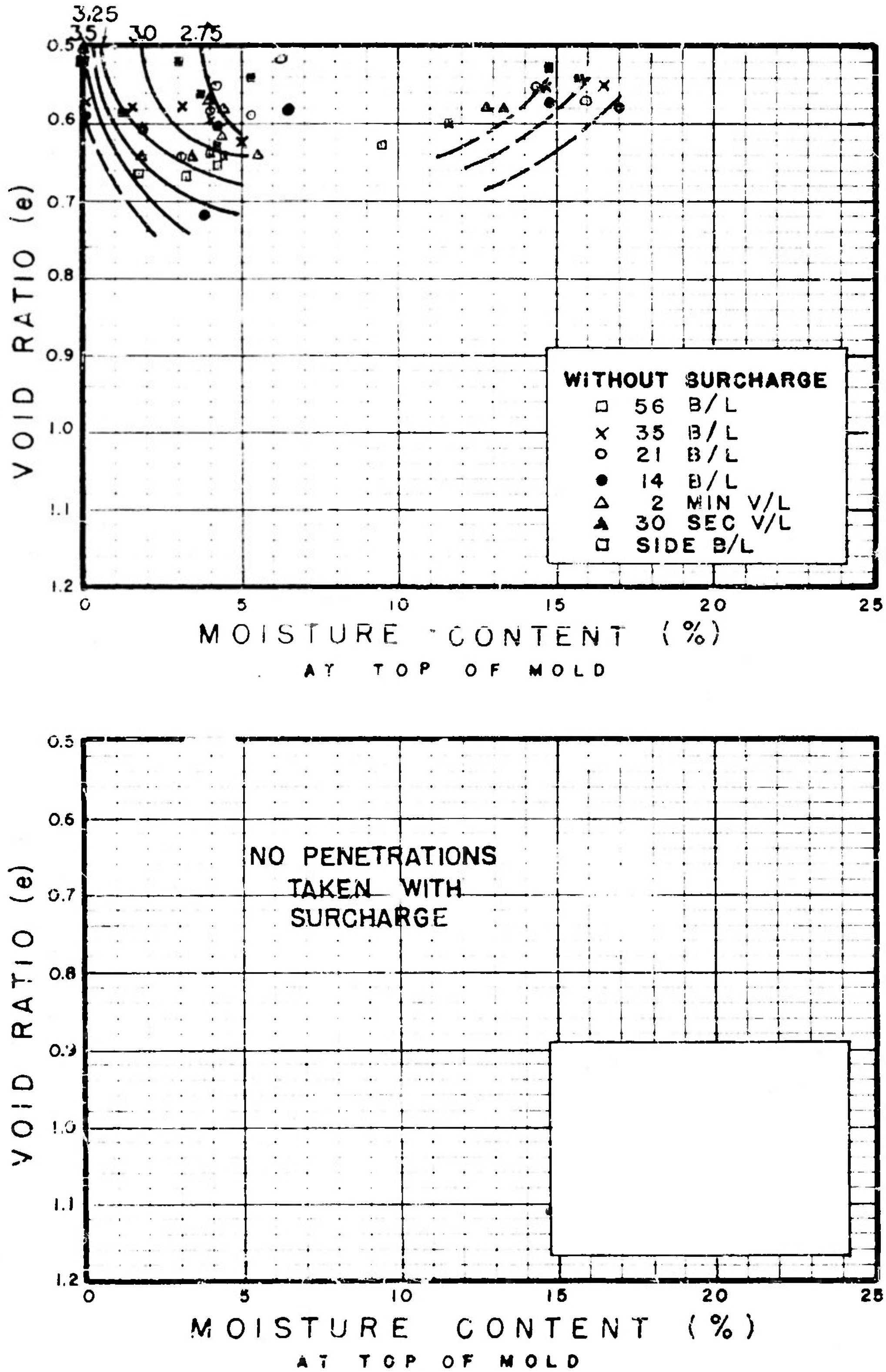
RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND F-12

FIGURE 7



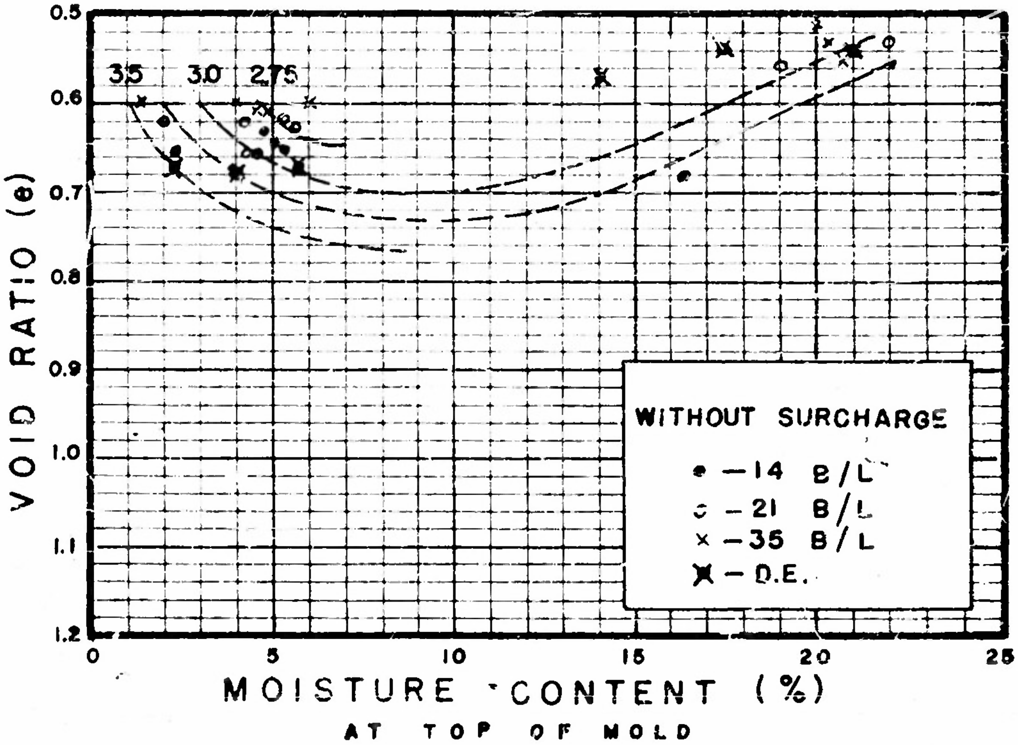
RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND NJ-20

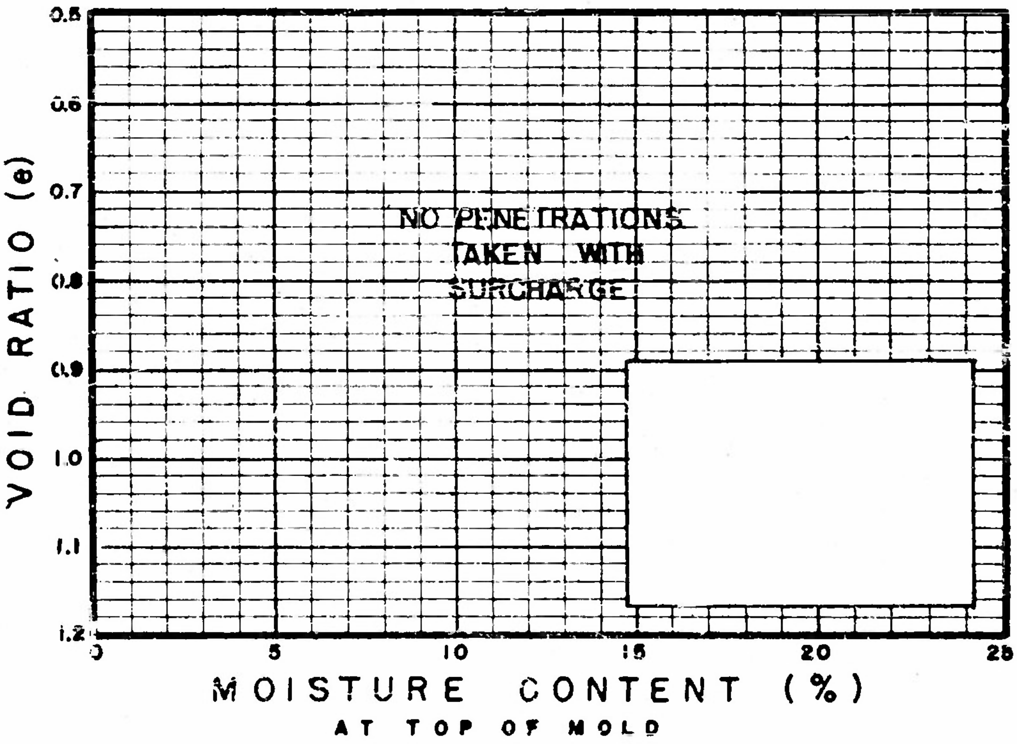
FIGURE 8



RELATIONS BETWEEN PENETRATION DENSITY
AND MOISTURE CONTENT SAND WT-3

FIGURE 9





RELATIONS BETWEEN PENETRATION DENSITY AND MOISTURE CONTENT SAND A

FIGURE 10

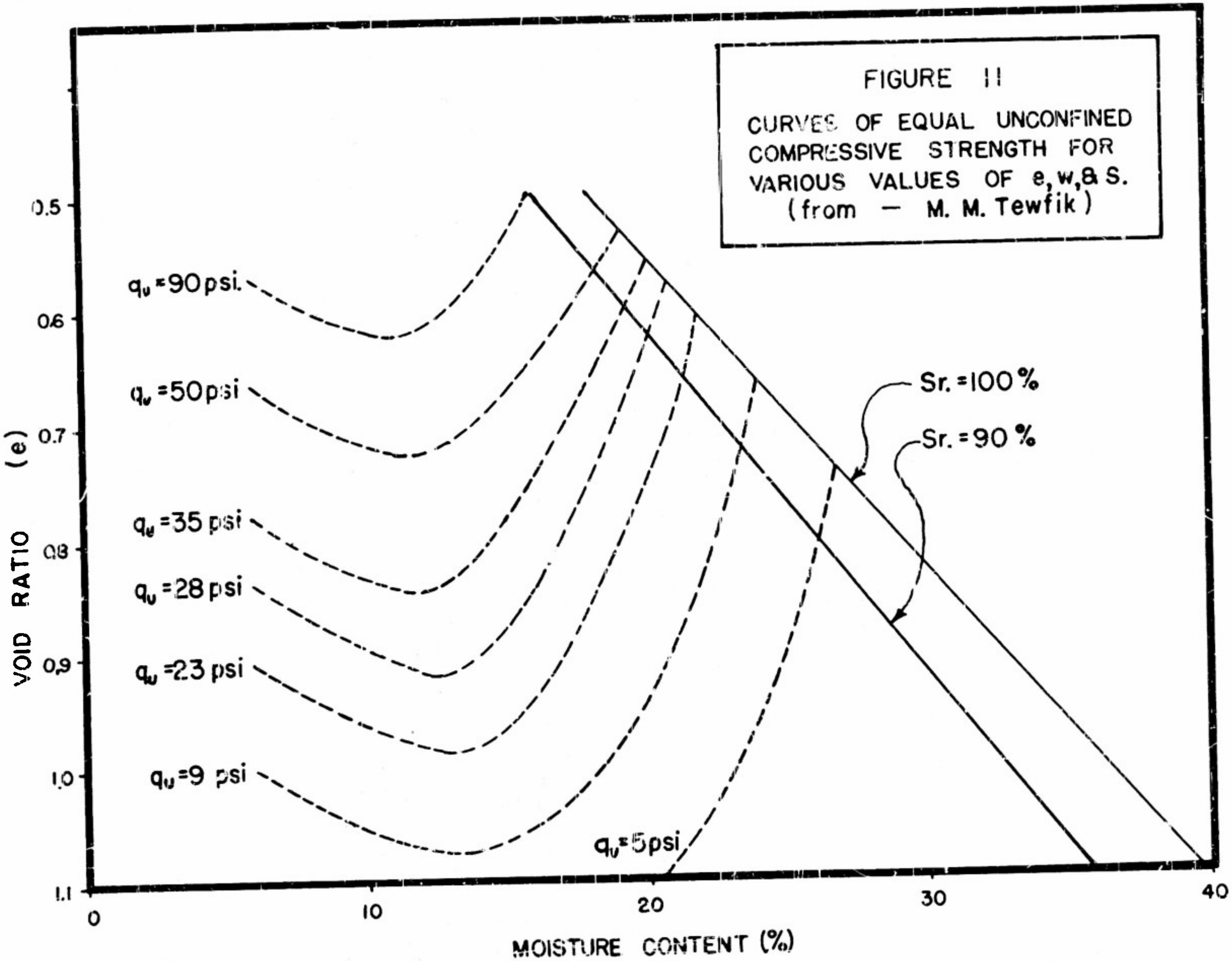


FIGURE 11

CURVES OF EQUAL UNCONFINED COMPRESSIVE STRENGTH FOR VARIOUS VALUES OF e, w, & S.
(from — M. M. Tewfik)

RELATIVE EFFECT OF
DENSITY AND MOISTURE ON PENETRATION

Figures 2 to 10 show that penetration <u>does vary in response to density, moisture and grain changes</u>. They also show that the relative amount of variation, for a given sample, depends upon the value of moisture or density that is chosen constant.

Because of the inter-relation between density, moisture and grain-size, a complete detailed evaluation of their relative influence on penetration is exceptionally tedious -- and beyond the scope of this report. Instead of such an evaluation, the report is concerned with general conclusions regarding such influence.

These general conclusions are discussed in the following pages.

<u>Effect of Density and Median Grain-Size</u>
<u>With w = 7.5%</u>

Figure 12 shows the variation of penetration with density, using a moisture content of 7.5%, for the entire field range of median grain-sizes. A value of w = 7.5% was selected for two reasons:

1. It is within, or close to, both the field and laboratory ranges for all samples.
2. It is midway between the moisture extremes associated with minimum penetration for all

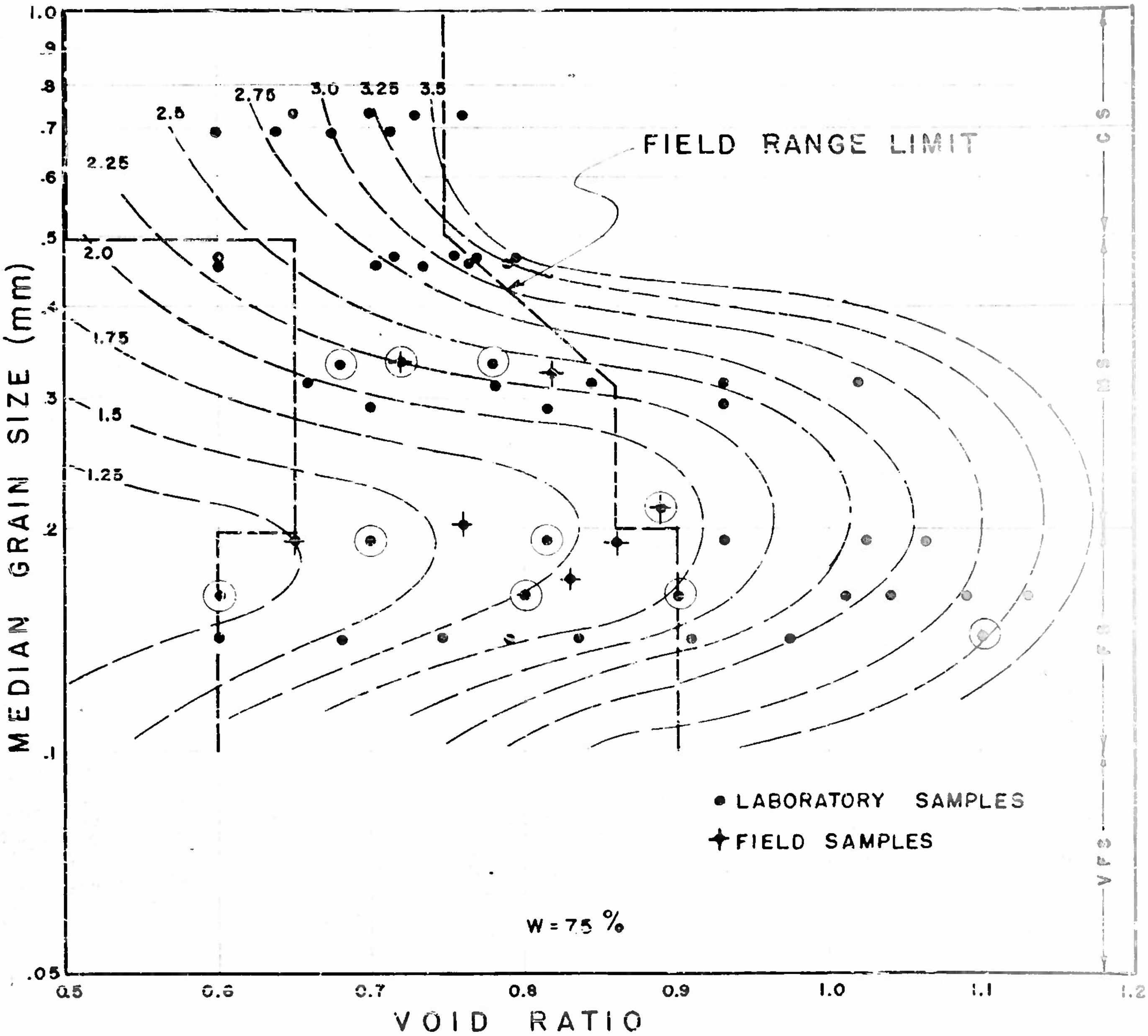


FIGURE 12

EFFECT of DENSITY and GRAIN SIZE on PENETRATION for w = 7.5%

samples, i.e., it is close to an average moisture content of presumed maximum shear strength for all median grain-sizes.

The degree of symmetry displayed by Figure 12 is surprising. It is true that the diagram was made with a considerable amount of extrapolation and that approximately 25% of the points do not fall near the proper lines. However, few of the points diverge from the lines by more that 1/4 inch of penetration and only three (2 from the field) diverge in excess of 1/2 inch. The symmetry is more surprising in view of the following facts:

1. The laboratory samples have uniformity coefficients ranging between 1.22 and 2.03 (see Figure 1) and a similar variety of gradations.
2. The samples have a variation in grain shape distributions.
3. Both laboratory (45) and field (9) points were plotted.
4. The field points included moisture contents that varied between 6.5% and 8.0% rather than the constant 7.5%.
5. The various laboratory samples were tested by several different groups of people with consequent slight differences in technique and results.

6. The diagram was derived from Figures 2 to 10 which in themselves insure a certain amount of divergence.
7. Penetrometer readings for the first series of samples and for the field points were read to the nearest 1/4 inch only.
8. The lines may be considered as the center of zones.

Since Figure 12, subject to all the discrepancies indicated by this series of variation factors, still maintains a great degree of symmetry and also reproduces experience in most of its areas, it is presumed to be generally correct (for w = 7.5%).

Effect of Moisture and Median Grain-Size with e = 0.7

Figure 13 shows the variation of penetration with moisture (e = 0.7) for the entire field range of median grain-sizes. A figure of e = 0.7 was selected because it was within, or close to, both the field and laboratory ranges for all samples. Unlike Figure 12, the pattern is asymmetrical. There are also more discrepancies. Nevertheless, there is a definite general order in the data (whose collection was subject to many of the variation factors listed for w = 7.5%) and the pattern fits the data in general. There is some reason to believe that a more symmetrical diagram would be better reconciled with experience. However, the data of these tests does not fit such a pattern.

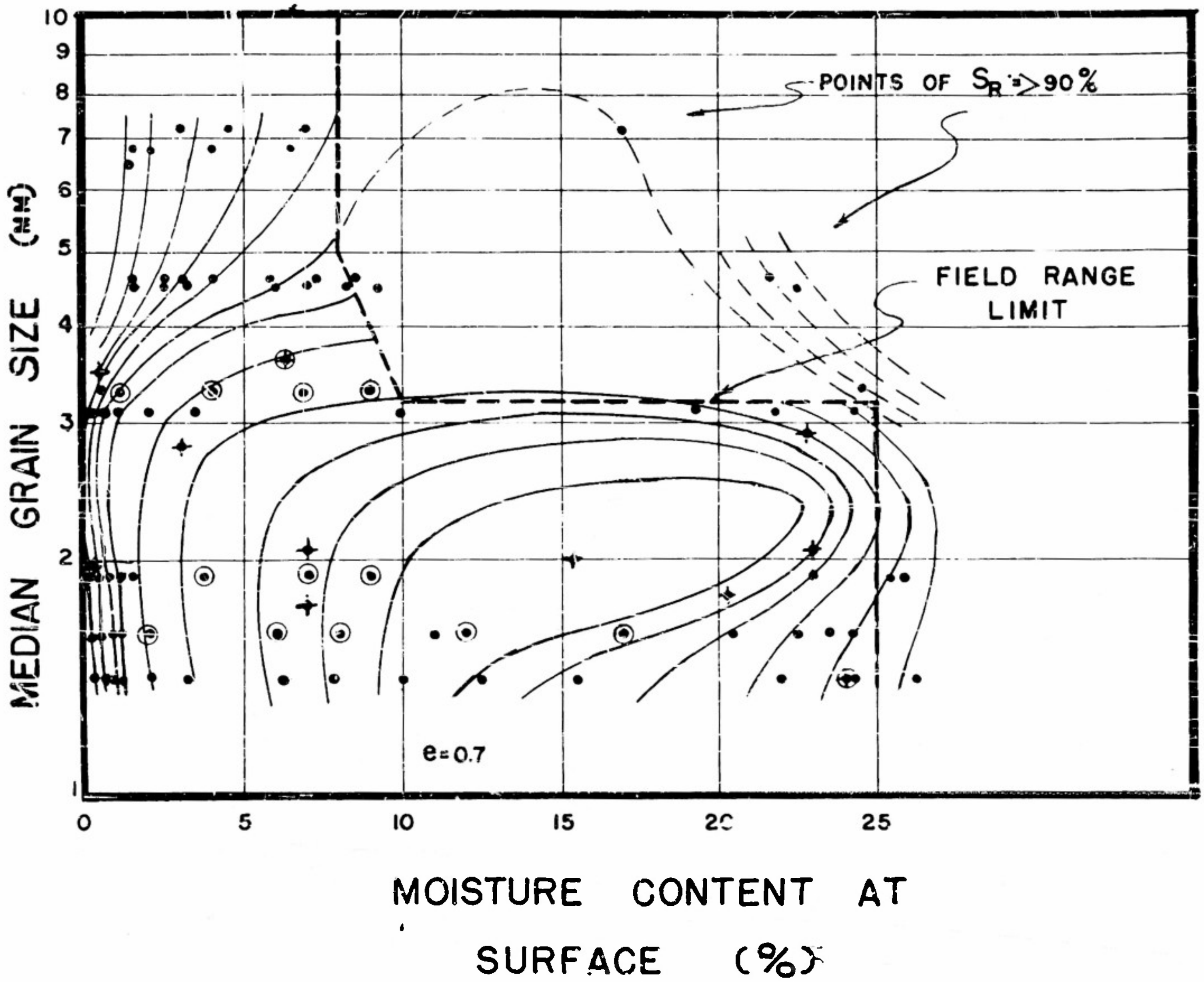


FIGURE 13

EFFECT of MOISTURE CONTENT and GRAIN SIZE on PENETRATION for e=0.7

General Statements Regarding the Relative Effects of Density and Moisture Content on Penetration for Sands of Various Median Grain-Size

As mentioned previously, due to the inter-relation of the various factors involved, a detailed evaluation of their relative effects on penetration would be exceptionally tedious. It would be necessary to construct Figure 12 for a series of moisture contents between zero and twenty-five. It would be necessary to construct Figure 13 for a series of void ratios between 0.6 and 0.9. Even then, the results would involve three independent variables, and it would be difficult to present them without resorting to tables or equations.

In the next few pages, a number of general statements are listed. Because of the difficulties mentioned above, the quantitative statements are limited to the conditions of Figures 12 and 13, the remaining statements being qualitative and based upon an examination of Figures 2 to 11.

For $w = 7.5\%$ within the range $e = 0.6$ to 0.9:

1. The effect of density on penetration is quite pronounced for the finer median sand sizes, beginning to decrease as sizes approach the medium range.
2. The effect continues to decrease until a size of 0.25mm is reached remaining constant to 0.30mm.

3. Beyond 0.30mm, the effect of density increases constantly (at least until size 0.72mm, the limit of the tests).

For e = 0.7 within the range w = 0 to 25%:

1. For fine sands and medium sands up to the 0.3mm size, the effect of moisture variation on penetration is relatively constant at a fairly high value.
2. For medium sands beyond 0.3mm and coarse sands, the effect decreases only slightly (assuming that moistures above 10% are obtainable -- a dubious possibility).
3. Recognizing that the moisture contents for coarse sands are either very low or near saturation, the practical effect of moisture on penetration is appreciably less.
4. For all sands, the effect of moisture on penetration remains at a fairly high level, particularly in the dry (0-5%) and very wet (22-25%) areas.
5. The effects of moisture are particularly important in fine sands and least important in coarse sands.

An examination of <u>all</u> the Figures in this report leads to a number of additional general statements regarding the relative effects of moisture and density on penetration:

1. Both moisture and density appreciably affect penetration in sands throughout the entire range of median grain-sizes.

2. For any given density, minimum penetrations in fine sands tend to be associated with moistures of 10% to 15% (S = 30-50%) in medium and coarse sands with moistures of 5% to 10% (S = 20-40%). (Figures 2 to 5).

3. Because of the relatively small range of moisture obtainable with coarse sands, the effects of moisture are not as important as with fine sands.

4. As sands become denser, lines of equal penetration seem to be associated with lines of constant saturation. (Figures 2 to 10).

SECTION III

CONCLUSIONS

GENERAL

The following conclusions are based primarily upon the results of tests described in this report. They also reflect the author's experience gained by participating in other phases of beach research. Only those major conclusions are included that are believed to be of practical value in using the other parts of this report.

In listing the conclusions, it is assumed (as described in preceding pages) that the capacity of beach sands to support wheel loads without excessive deformation is related to the shearing strength of the beach sands. In turn, it is assumed that the shearing strength is a function of the combined effect of moisture, density and grain characteristics.

CONCLUSIONS

1. Constant weight penetration is appreciably affected by variations in both density and moisture for sands of all median grain-sizes.
2. The amount of penetration is a function of the moisture, density and grain characteristics acting around the locale of penetration. Consequently, for sands in general, there are an infinite number of moisture-density-grain combinations and -- for a given sand -- an infinite number of moisture-density combinations that will yield the same penetration.
3. Because the constant weight penetrometer <u>does</u> reflect the combined effect of moisture, density and median grain-size, <u>it is a valid instrument</u> for measuring an index of the capacity of beach sands to support wheel loads without excessive deformation. In view of its many advantages, it appears to be a highly useful instrument for this purpose.
4. Because of the infinitude of moisture-density-grain combinations, the difficulty of evaluating single penetration readings is apparent. Unless data is available concerning moisture, density, grain characteristics -- or secondarily, slope or width -- it is possible to come to the erroneous conclusion that single penetrations are excessively erratic. This conclusion is the result of insufficient data rather than inaccurate measurement. Consequently, although some

erratic penetration readings may be expected, particularly in very dry, very wet or coarse sands, the assumption of excessive erraticism appears unfounded.

6. For the range of median grain-sizes commonly occurring on sand beaches, moisture changes tend to have a greater effect on penetration than density changes. This is particularly true for fine sands and is least true for coarse sands.

7. Density changes are most effective in the coarser sand sizes.

8. Some of the conclusions of VOLUME I*, to the effect that low penetrations are associated with fine grain-sizes and high penetrations with coarse sizes, are corroborated by the data of these tests.

9. There are indications that materials smaller than fine sands would yield constant-weight penetrations having the same order of magnitude and pattern of variation as medium and coarse sands.

10. Penetrations of all sands at saturations greater than 90% are likely to be greater than 2.5 inches, but less than 3.75 inches. In general, the penetrations of the finer, highly saturated sands will be slightly lower than those of coarser highly saturated sands. A certain amount of erraticism may also be expected.

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*See KEY following Title Page.

APPENDIX A

TEST, COMPUTATION

AND ANALYSIS PROCEDURES

TEST PROCEDURES

The test apparatus was essentially an oversized Proctor mold (base, main cylinder and collar), with an oversized hammer and hammer guide.

Each sample was tested in the following manner:

1. The mold was filled 1/3 full (2") from a 50 lb. mixed and quartered stock pile to which had been added an amount of moisture necessary to bring the percentage of moisture to a desired figure (0, 3, 6, 9, 12, 15, 18 and 20% were the successive goals in every test series).
2. The layer of sand was compacted. The method of compaction depended upon the test that was being run (see Figures 2 to 10). The following methods were used;
    a. Loose (sand poured from a slight elevation).
    b. Dropped on edges (twice per layer from an elevation of 6" at an angle of 45°-60°).
    c. 14 blows/layer (rotating the mold).
    d. 21 blows/layer (rotating the mold).
    e. 35 blows/layer (rotating the mold).
    f. 10 hammer blows/layer on the outside of the mold (rotating the mold).
    g. 30 seconds vibration/layer with a concrete vibrator.

h. 2 minutes vibration/layer with a concrete vibrator.

3. A second and third layer of sand was added, compacted and (for the top layer) evenly struck off with the collar removed.

4. The mold, with sand and water, was weighed.

5. Three constant-weight penetrations, equally spaced over the surface of the top layer were taken. Two were taken without surcharge and one was taken through a standard annular lead CBR surcharge. (At first, penetrations were taken to the nearest 1/4 inch, later to the nearest 1/10 inch.

6. Five moisture content samples were taken, one at each point of penetration, one halfway down in the mold, and one near the bottom of the mold. The method of moisture content determination was that described in ASTM Designation D426-39.

7. The sample was dumped back into the stock pile, mixed and the next desired amount of water added. After mixing and quartering, the entire procedure was repeated (9 samples, 8 moisture contents, an average of 5 compactive efforts, a total of 350-400 tests).

8. At the beginning and conclusion of each compactive effort series (except vibration, loose and dropping on edges), grain-size analyses were made on a representative sample from the mold. ASTM Designation D422-39 was used as a method.

9. A true specific gravity was obtained for each sample used. ASTM Designation D854-45T was used as a method for this determination.

COMPUTATIONS

Following the completion of each test, the following quantities were computed:

1. Moisture contents (% of dry weight).
   a. Average for the surface (w_{t_a}).
   b. Middle of the mold (w_m).
   c. Bottom layer of the mold (w_b).
   d. Average content for the entire mold according to Simpson's Rule (w_{a_s}).
2. Total weight of mold plus sample plus water (Wt).
3. Total weight of water (Ww).
4. Total weight of solids (Ws).
5. Total volume of cylinder (Vt).
6. The void ratio-presumed for the cylinder as a whole (e).
7. True specific gravity (G).
8. Degree of saturation at the top (St).
9. Average wet density (γw).
10. Average dry density (γd).
11. Average penetration without surcharge (P).
12. Penetration with surcharge (Ps).
13. Grain-size distribution curve
14. Median grain-size (D_{50}).
15. Effective grain-size (D_{10}).
16. Uniformity coefficient (Uc).

No special techniques were used in obtaining the above quantities.

ANALYSIS PROCEDURES

The following diagrams were plotted for each sample from the computational data:

1. Moisture (w_a) versus Wet Density (w) for each compactive effort.
2. Moisture (w_a) versus Dry Density (γd) for each compactive effort.
3. Void-ratio (e) versus Moisture (w_{ta}) with coincident Saturation (St) and Penetration without surcharge (P). (These plots appear as Figures 2 to 10).
4. Same as 3 but with Penetration with surcharge (Ps). (These plots appear in Figures 2 to 10).
5. Penetration (P) versus Moisture (w_{ta}) for each compactive effort.
6. Penetration (P) versus Average Dry (γd) and Average Wet Density (γw) for each compactive effort.

No special techniques were used to obtain the above plots.

APPENDIX B

FORMULAS USED TO OBTAIN VARIOUS QUANTITIES

1. Moisture Contents

a. General: $w = \frac{Ww}{Ws} \times 100$

b. At surface: $w_{t_a} = \frac{w_{t_1} + w_{t_2} + w_{t_3}}{3}$

c. Average for mold: $w_{a_s} = 1/6\ (w_{t_a} + 4w_m + w_b)$

2. Weights

a. Weight of solids: $Ws = \frac{Wt}{1 + w_{a_s}}$

b. Weight of water: $Ww = Wt - Ws$

3. Void Ratio (Centigrade System)

$$e = \frac{(VtG)(1 + w_{as})}{Wt} - 1$$

4. True Specific Gravity

a. Pycnometer Method: $G = \frac{Ws}{W_1 + W_s + W_2}$

5. Saturation

a. At top: $S = \frac{w_{t_a}\ G}{e}$

6. Densities (English System)

a. Wet: $\gamma_w = \frac{Wt}{Vt}$

b. Dry: $\gamma_d = \frac{w}{1+w}$

7. Uniformity Coefficient

$$Uc = \frac{D_{50}}{D_{10}}$$

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